Effects of post annealing treatments on the characteristics of ohmic contacts on n-type AlGaN

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ABSTRACT

In this work, we investigate the thermal stability and surface morphology of Ti metal contact on unintentionally doped n-type aluminum gallium nitride (AlGaN). Different annealing temperatures (400°C - 800°C) and durations (1 - 30 minutes) are investigated, as thermally stable metal-semiconductor contacts are essential for high quality devices. Cryogenic quenching after heat treatment is also performed to determine the effects of this treatment on the characteristics of the contacts. Specific contact resistivity, ρ_c (SCR) determined using transmission line method (TLM) and scanning electron microscopy (SEM) measurements are carried out to the as-deposited, annealed (*A*), and annealed-and-cryogenically (*A+C*) treated contacts where the electrical behavior and the surface morphology of each of these conditions are compared. The result shows that cryogenic treatment is able to reduce the SCRs after annealing as most of the *A+C* samples exhibited lower SCR as compared to *A* samples. For relatively low annealing temperatures, i.e. 500°C and below, the difference of SCR values between *A* and *A+C* treated samples is insignificant, however, when the samples are thermally treated at higher temperatures, i.e. 600°C and above, substantial difference of the SCR values is observed between *A* and *A+C* treated samples. SEM images indicate that little difference of surface morphology is observed for all the samples regardless of the annealing temperatures, durations and treatments. The *A+C* sample annealed at 600°C for 2 minutes is found to be able to yield the lowest SCR in this study.

Keywords: n-AlGaN, ohmic contact, cryogenic treatment, transmission line method

1. INTRODUCTION

The wide band gap semiconductors of the nitrides belonging to the III-V family, such as gallium nitride (GaN) and related alloys, have received enormous attention for their broad range of practical applications. In particular, the ternary compound AlGaN has potential for the fabrication of optoelectronic devices such as light emitting diodes (LEDs), and laser diodes (LDs), covering nearly the entire deep-UV spectral region, as well as high power, and high frequency electronic devices operating at high temperatures. Despite recent significant progress in the development of GaN-based devices, central to their performance, however is the quality of metal contacts. As the semiconductor device technology advances, more stringent requirements are needed for the fabrication of ohmic contacts with very low resistance (reducing knee voltage and resistive heating), good thermal stability (ensuring dependable high temperature performance), and flat surface morphology (hence good edge acuity for short channel devices) [1]. It is widely known that parasitic resistances, in the form of contact resistance, significantly affect the overall performance of the electronic and optical devices. The large voltage drop across the semiconductor/metal interface at the ohmic contacts will seriously lead to the loss of device performance and reliability. Therefore, high quality, thermally stable contacts to GaN-based materials are essential for the fabrication of reliable, efficient, high performance devices and circuits.

A wide variety of metallizations for ohmic contacts on n-GaN have been intensively investigated. From the literature, contact resistances below 10^{-5} Ω-cm^2 can be achieved routinely and low contact resistance as low as 10^{-8} Ω-cm^2 has been reported [2,3], which is good enough for the optical and electronic devices. However, it is difficult to achieve low contact resistance on AlGaN due to the Schottky barrier height of many metals on AlGaN being larger than 1 eV [4]. The best specific contact resistivity on n-AlGaN is several orders of magnitude higher than on n-GaN [5]. Therefore there is still a challenge in developing reliable ohmic contact with low contact resistivity on n-AlGaN.

The ohmic formation mechanism for Ti based contact on GaN or AlGaN has long been suggested to be resulted from the solid phase interaction between Ti and GaN to form TiN which is metallic in nature; this leads to the outdiffusion of N atoms from GaN and an accumulation of N vacancies near the surface is created which acts as donors, eventually a heavy n-doped region is formed and this facilitates the formation of good ohmic contact [1, 6 - 9]. Many reported [1, 8] that the interfacial TiN phases were observed at contact and semiconductor interface, however, the reports were based only on the observation of transmission electron microscopy (TEM) images and energy dispersive x-ray spectroscopy. Since the interfacial phases are in such fine scale microstructures, identification of various phases is difficult[1]. Furthermore nitride phase has similar structure to AlGaN, thus only few results can be obtained by x-ray diffraction (XRD) patterns and TEM selected area diffraction patterns [10]. In this work, instead of the investigation of the formation of interfacial phases, we studied and compared the electrical behavior of the contacts under two different thermal treatments at various temperatures.

It is widely known that the application of thermal treatment is vital in achieving ohmic contact upon metal deposition to the wide bandgap semiconductor since there are very few as-deposited metals, which have ohmic behaviour. In fact, thermal treatment has been used to study the thermal stability in many metal-semiconductor contacts as well as to improve or optimize the electrical properties of the contacts. Thermally stable metal-semiconductor contacts are essential for the realization of high quality devices. However, there are very few cases where cryogenic treatment is used as a way to improve the electrical properties of metal contacts after thermal treatment. Mi-Ran Park *et al* [11] has successfully used this method (cryogenic cooling after heat treatment) in reducing the specific contact resistance in Ni/Au contact from 9.84×10^{-4} Ωcm^2 to 2.65×10^{-4} Ω-cm^2.

In this paper, investigations on the electrical and structural characteristics of Ti contacts on unintentionally doped n-type AlGaN are presented. Different annealing temperatures (400°C-800°C) and durations (1-30 minutes) were investigated, as thermally stable metal-semiconductor contacts are essential for high quality devices. Cryogenic cooling right after heat treatment was also carried out to assess and determine the influence of this treatment on the characteristics of the contacts. Specific contact resistivity (SCR) determined using transmission line method (TLM), and scanning electron microscopy (SEM) measurements were performed onto the annealed (*A*), and annealed-and-cryogenically (*A+C*) treated contacts where the electrical behavior and the surface morphology of each of these conditions were compared.

2. EXPERIMENTAL

In this study, unintentionally doped n-AlGaN (~24% of AlN mole fraction) epilayer with thickness of 1.1 μm grown on sapphire substrate was used. The carrier concentration of the wafer is about 10^{16} to 10^{17} cm^{-3}; and the resistivity of wafer measured by four-point probe was found to be 41.5 Ω-cm. The ohmic contact, Ti with thickness of 150 nm was deposited onto the AlGaN through a metal mask by using a sputtering system. Prior to the metal deposition, the native oxide was removed in the NH_4OH: H_2O = 1:20 solution, followed by HF:H_2O = 1:50. Boiling aqua regia (HCl: HNO_3 = 3:1) was used to chemically etch and clean the samples.

The samples were divided into two sets. The first set of samples were annealed *(A)* under flowing nitrogen gas environment in a furnace at temperatures ranging from 400°C-800°C for different durations. Second set of samples were annealed under similar conditions, however, the samples were cooled by dipping into liquid nitrogen right after annealing *(A+C)*, then they were brought to room temperature in air. This was done to study the effect of cryogenic cooling treatment. Heat treatment (*A* or *A+C*) was carried out again after performing current-voltage (I-V) measurements for the subsequent annealing to investigate the thermal stability of the contacts. Changes in the surface morphology of the contacts with different annealing temperatures were examined by using scanning electron microscopy (SEM).

The transmission line method (TLM) pads were 2mm (*W*, width) ×1 mm (*d*, length) in size, and the spacings, *l*, between the pads were 0.3, 0.4, 0.6, 0.9 and 1.3 mm. The specific contact resistivities, ρ_c were determined from the plot of the measured resistances against the spacings between the TLM pads. The linear-square method was used to fit a straight line to the experimental data.

3. RESULTS AND DISCUSSION

3.1 Electrical characteristics

3.1.1 Current-Voltage measurements

Fig. 1 shows the I-V characteristics of two *A* and *A+C* samples thermally treated at 600°C under annealing durations of 2 and 5 minutes (cumulated 7 minutes), respectively. This particular annealing temperature was chosen to present the I-V characteristics because this is the optimum annealing temperature which produced the lowest SCR under 2 minutes *A+C* treatment. For the *A* sample, when annealed for 2 minutes, near ohmic behavior was observed, and it showed little difference when the sample was further annealed for 5 minutes (cumulated 7 minutes). On the other hand, sample under *A+C* treatment for 2 minutes exhibited ohmic behavior, however when the sample was brought for subsequent *A+C* treatment for 5 minutes (cumulated 7 minutes), ohmic behavior started to degrade where a slight non-linear I-V characteristic was observed. From Fig. 1, *A+C* samples generally showed a lower resistance as compared to *A* samples at 600°C. The effect of cryogenic treatment on improving the contact resistance could be attributed to some of the semiconductor dissolving in the Ti metal on heating and recrystallization with a high concentration of the electrically active element in the solid solution on the subsequent cooling [12].

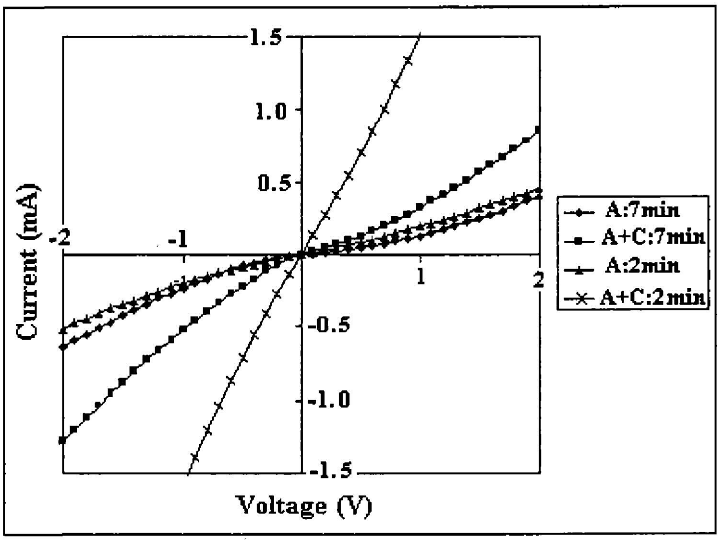


Fig. 1 The I-V characteristics of two samples annealed at 600°C under *A* and *A+C* treatments for 2 and 7 minutes

3.1.2 Specific contact resistivity

The measurements of the specific contact resistivity were made using the TLM method that has been widely used in the characterization of ohmic contacts to semiconductors. Resistance, R_i, between two contacts with spacing l_i, is given by

$$R_i = \frac{R_{sh} l_i}{W} + \frac{2 R_{sk} L_t}{W} \tag{1}$$

$$R_i = \frac{R_{sh} l_i}{W} + 2R_c \tag{2}$$

where W is the width of the pad, R_c is resistance due to contact, R_{sh} is sheet resistance of the semiconductor layer outside the contact region, R_{sk} is the sheet resistance of the layer directly under the contact, and L_t is the transfer length.

The plot of R_i as a function of l_i will produce a straight line with a slope of R_{sh}/W, and $2R_c$ is yielded from the intercept at y-axis. The intercept at x-axis, will give L_x, where

$$L_x = \frac{2R_{sk}L_t}{R_{sh}} \approx 2L_t \quad (3)$$

with the assumption that $R_{sh}=R_{sk}$ [13]. On the other hand, the assumption of an electrically long contact $d>>L_t$ enabled the relationship $\rho_c = R_{sh}L_t^2$ to be invoked [14], which leads to $\rho_c = R_c W L_t$.

In this study, heat treatments could be divided into low (400°C), moderate (500 - 600°C) and elevated (700 - 800°C) annealed temperatures. The Ti contact resistivities measured in this study are summarized in Table 1. The initial investigation revealed that all as-deposited samples demonstrated Schottky behavior.

For low annealing temperature, i.e. 400°C, both *A* and *A+C* treated samples exhibited Schottky behavior for annealing duration of 5 minutes, however for the subsequent annealing, ohmic characteristics were observed. This might be due to the contact metal consuming part of the barrier or interfacial contamination between metal and AlGaN to form a conducting metallic phase, therefore this led to a thinner barrier in contact with the metal-nitride layer. On the other hand, 500°C (*A* and *A+C*) samples started showing ohmic behavior after brief annealing for 2 minutes. Generally, for relatively low annealing temperatures i.e. 500°C and below, we notice that the difference of the SCR values between *A* and *A+C* treated samples is insignificant.

Table 1: The specific contact resistivities at different annealing temperatures and times

Annealing Temperature		Specific Contact Resistivities (Ω-cm^2)		
Low Temperature		Time/(cumulated time)		
		5 min	10 min/(15min)	15 min/(30 min)
400°C	A	Sch.	1.73	1.11
	A+C	Sch.	1.54	1.83
Moderate Temperature		Time/(cumulated time)		
		2 min	5 min/(7min)	-
500°C	A	0.50	0.63	-
	A+C	0.49	0.77	-
600°C	A	0.62	0.67	-
	A+C	2.8×10^{-2}	0.17	-
Elevated Temperature		Time/(cumulated time)		
		1 min	2 min/(3 min)	-
700°C	A	0.50	9.1×10^{-2}	-
	A+C	3.3×10^{-2}	4.8×10^{-2}	-
800°C	A	0.13	*	-
	A+C	6.8×10^{-2}	*	-

Sch.: Schottky behavior.
* The ohmic characteristics deteriorated under this condition. Hence no data was obtained.

When the samples were thermally treated at higher temperatures, i.e. 600°C and above, substantial difference of the SCR values was observed between samples under *A* and *A+C* treatments. For *A+C* samples, SCR values obtained in the initial treatments was found to be lower as compared to the subsequent treatment. On the other hand, both *A* and *A+C* samples treated at elevated temperature, i.e. 800°C, showed deterioration after the subsequent 2 minutes (cumulated 3 minutes) thermal treatment was introduced. I-V measurements could not be obtained for this annealing condition because the samples were too resistive, this could be mainly attributed to the formation of oxides. Although the samples were annealed in nitrogen ambient, a certain amount of oxygen could be present in the furnace which would lead to the formation of oxide compounds such as Ga_2TiO_5 and/ or γ-$Ga_2Ti_2O_7$ in the samples under high annealing temperature; this has been claimed and reported by E. F. Chor [15]. Generally, the samples under *A+C* treatment were found to exhibit better SCR values than *A* samples. In our previous investigation [16], we have also reported that Ni/Ag contacts on p-GaN demonstrated lower SCR by the use of cryogenic treatment, similar finding also claimed by Mi-Ran Park *et al* [11] in which the effect of cryogenic treatment indeed could be employed to enhance the ohmic behaviour and SCR.

Fig. 2 shows the best SCR value of *A* and *A+C* samples for each of the annealing temperature (data extracted from Table 1). In this study, the lowest SCR value obtained was 600°C (*A+C*) annealed for 2 minutes. From Fig. 2, for *A* samples, SCR decreased from 400 to 500°C annealing temperature, and followed by a relatively consistent values at around 0.5 Ω-cm^2 from 500 to 700°C before it further decreased at 800°C.

On the other hand, for *A+C* samples, the SCR values decreased from 400 to 600°C, in between, a sharp reduction of SCR was observed from 500 to 600°C; where it reached the lowest SCR at 600°C, followed by a gradual increasing trend from 600 to 800°C.

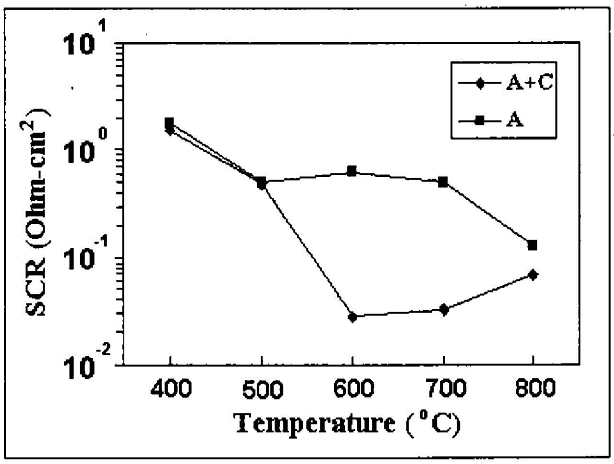


Fig. 2. The variation of SCR of *A* and *A+C* samples as a function of annealing temperature

3.2 Surface morphology

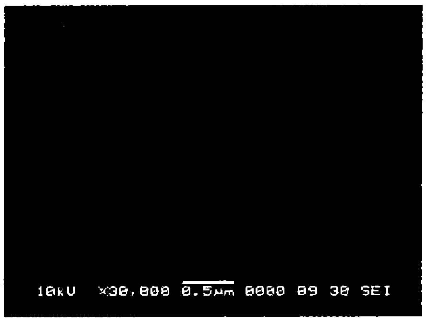
The observation by SEM reveals a relatively good surface morphology for all the samples in this study regardless of the annealing temperatures, durations and treatment. Fig. 3 shows some of the selected SEM images of the samples; *A* and *A+C* samples annealed at low, moderate, and elevated temperatures, i.e. 400°C, 600°C and 800°C for duration of 15 min (cumulated 30 min.), 5 min. (cumulated 7 min.) and 2 min. (cumulated 3 min.), respectively. Generally, no agglomeration or "ball-up" was observed from the SEM images for all of the samples. This observation contradicts with our previous finding [17], in which Ti metal contacts on n-GaN experienced agglomeration when annealed at 800°C for 15 min. The difference in observation could be partly due to the introduction of relatively short annealing durations for samples annealed at moderate and elevated temperatures which allowed no adverse impact on the surface morphology. On the other hand, for low temperature, i.e. 400°C, long annealing duration is not detrimental to the surface morphology too. It has been reported that Ti is of appreciable importance in forming stable contacts; it provides good adhesion to the GaN surface. The presence of Ti or Ti alloys at the interface also provides mechanical stability to the contacts [18]. Therefore samples under short duration of high annealing temperatures or long duration of low annealing temperature show no deterioration of the surface morphology.

When visual check was performed on the samples, the change of color of the contacts was observed. For instances, *A* and *A+C* samples treated at 600°C showed various colors under different annealing durations. The as-deposited sample showed silver color. For *A* sample, after 2 minutes annealing, it demonstrated gold color, and the subsequent 5 minutes (cumulated 7 minutes) annealing exhibited semi-transparent color. On the other hand, *A+C* sample showed purplish complexion for the initial 2 minutes thermal treatment, followed by blue color after the subsequent 5 minutes annealing. This strongly suggested that the change of solid phases of the contacts had been taking place during the thermal treatment. Although different colors were observed for the *A* and *A+C* samples under similar annealing temperature and duration, substantial difference were found in SCR values between the *A* and *A+C* treated samples; this indicated that *A* and *A+ C* treatments could produce different interfacial phases which led to the difference in electrical behaviors eventually.

(a) 400°C: *A*

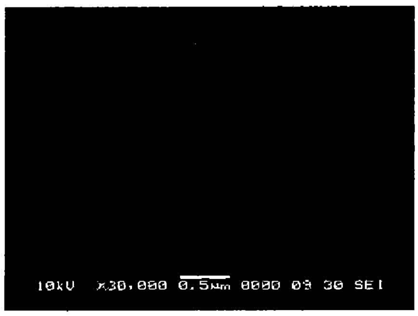
(b) 400°C: *A*+*C*

(c) 600°C: *A*



(d) 600°C: *A*+*C*

(e) 800°C: *A*



(f) 800°C: *A*+*C*

Fig. 3 SEM images of the Ti contacts annealed at different temperatures and treatments: (a) *A* sample annealed at 400°C for total 30 minutes; (b) *A*+*C* sample annealed at 400°C for total 30 minutes (c) *A* sample annealed at 600°C for total 7 minutes; (d) *A*+*C* sample annealed at 600°C for total 7 minutes; and (e) *A* sample annealed at 800°C for total 3 minutes, (f) A+C sample annealed at 800°C for total 3 minutes. Scale bar indicates 0.5 μm.

CONCLUSION

The thermal stability, electrical behavior and surface morphology of Ti contacts on n-AlGaN at various annealing temperatures (400°C - 800°C) have been investigated. The experimental result showed that cryogenic treatment after annealing is able to reduce the SCRs as most of the *A+C* samples exhibited lower SCR as compared to *A* samples. For relatively low annealing temperatures, i.e. 500°C and below, the difference of SCR values between *A* and *A+C* treated samples was found to be insignificant, however, when the samples were thermally treated at higher temperatures, i.e. 600°C and above, substantial difference of the SCR values was observed between *A* and *A+C* treated samples. SEM images indicated that little difference of surface morphology was observed for all the samples regardless of the annealing temperatures, durations and treatments. The lowest SCR obtained in this study was found to be $2.8 \times 10^{-2}\ \Omega cm^2$ for the *A+C* sample annealed at 600°C for 2 minutes.

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